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The relationship between fire activity and fire weather indices at different stages of the growing season in Finland

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This study examines the relationship between predicted fire hazard and observed fire activity at different stages of seasonal vegetation development. The data consisted of Finnish national fire records 1996–2003, the daily values of the effective temperature sum of over 5 °C, the Finnish Fire Risk Index, and the FWI and ISI codes of the Canadian Fire Weather Index System. The highest probabilities for fire-day and multiple-fire-day occurrence were found during the final stage of the growing season, at the temperature sum value of above 900. The probability of large-fire-day was highest during the early stages of the growing season. The statistical significance of the probability models was poorest during the initial and final stages of the season.

Introduction

The occurrence and behavior of forest fires is mainly a product of weather and fuel conditions (e.g. Byram 1959, Fosberg *et al*. 1970, Rothermel 1972, Albini 1976). Weather affects fire behavior directly during the burning process (Rothermel 1972) but also indirectly through the formation of the fuel conditions, especially fuel moisture (Fosberg *et al*. 1970). Structural fuel characteristics, such as the site-specific composition and arrangement of fuel material and seasonal processes of plant growth and curing, may greatly influence fire behavior, and during certain periods, override weather-based fire danger implications (Countryman 1974, Albini 1976).

Burning conditions can currently be assessed and predicted with various weather-based indices, such as the Fire Weather Index (FWI) component of the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner 1987, Stocks *et al*. 1989), the Fire Behavior Prediction and Fuel Modeling System (BEHAVE) (Andrews 1986), and the Finnish Forest Fire Risk Index (FFI) (Heikinheimo *et al*. 1998, Venäläinen and Heikinheimo 2003). The functions of weather-based indices are focused on the assessment of surface fuel moisture (Van Wagner 1987, Stocks *et al*. 1989) because it affects the ignition, spread, and fuel consumption of forest fires (Byram 1959, Rothermel 1972, Albini 1976, Nelson 2001). In addition to fuel moisture content, most fire danger rating systems incorporate the effect of wind on fire behavior into their danger ratings (e.g. Van Wagner 1987, Stocks *et al*. 1989).

The main weakness of the models is that they can only give a generalized view on fuel conditions based on the dead fuel component of the material present. In fine dead fuels, moisture content is in large part controlled by surrounding weather conditions i.e. relative humidity, air temperature, wind, solar radiation, and the amount of precipitation (Van Wagner 1979, Van Wagner 1987, Nelson 2001). Fine live fuel moisture does not respond to short-term weather but shows long-term variation caused by phenological changes taking place in plants over the fire season (e.g. Blackmarr and Flanner 1968, Loomis and Blank 1981, Rice and Martin 1985, Brown *et al*. 1989, Viegas *et al*. 2001). Fine live fuels exhibit remarkably higher moisture contents than fine dead fuel material and are for this reason considered as a sink of heat and a fire retardant (Burgan 1979, Sylvester and Wein 1981, Burgan and Rothermel 1984). The growth and curing of major live fuel components have been incorporated as dynamic fuel models into the BEHAVE System (Scott and Burgan 2005). The standard version of the FWI (Van Wagner 1987) or the FFI (Heikinheimo *et al*. 1998) do not include a function for the estimation of seasonal vegetation development, probably due to the fact that these systems operate in fuel types that do not present the pronounced curing period characteristic to temperate grasslands.

In Finland, approximately 86% of the land area is covered by forest, and nearly 57% of the forest area is dominated by *Pinus sylvestris* (Scots pine) and 32% by *Picea abies* (Norway spruce) (Finnish Statistical Yearbook of Forestry 2000). Finland belongs to the boreal zone (Ahti *et al*. 1968), where fire is considered the principal natural process responsible for the renewal of forests (Rowe and Scotter 1973, Goldammer and Furyaev 1996). Fire has historically had a strong impact on the Finnish landscape but as a result of developing infrastructure, technical improvements in fire suppression efficiency, and the abandonment of traditional fire use practices, both the average fire size and yearly area burned has diminished dramatically in Finland during the 20th century (Parviainen 1996). The extent of natural and controlled fires in this ecosystem is currently so small that many fire-dependent species have become endangered (Rassi *et al*. 2003).

Moss mixed with litter is the principal material in which fire spreads in Finnish forests (Van Wagner 1983, Schimmel and Granström 1997). The most abundant moss species in Finland is the circumpolar feather moss *Pleurozium schreberi* (Mäkipää 2000). Above the moss, there is a sparse vascular understory vegetation layer featuring low *Ericaceous* shrubs, such as *Vaccinium myrtillus*, and *Vaccinium vitis-idaea*, tall robust forbs like *Epilobium angustifolium*, or low annual grasses. *Vaccinium myrtillus* is a deciduous dwarf shrub with ever-green stem, whereas *Vaccinium vitis-idaea* also has evergreen leaves. These two dwarf shrubs are characteristic understory species for the most common site types in the Finnish forest site type classification (Cajander 1926). *Epilobium angustifolium* is common in clear-cuts and has been rated to have a very low fuel potential due to its high moisture content (Sylvester and Wein 1981). The spatial arrangement of live understory vegetation is usually too sparse for this layer to act as primary fire carrier under any fuel moisture conditions. If abundant, understory vegetation may, however, decrease or increase fire spread and intensity in the moss layer.

In Finland, precipitation is ample and regular throughout the year (Drebs *et al*. 2002) and the seasonal growth of plants is mainly driven by temperature (Kramer *et al*. 2000). The timing of many phenological phenomena such as flowering of trees or maturing of crops can effectively be predicted using effective temperature sum (e.g. Sarvas 1972) which is the cumulative sum of daily mean air temperature above a certain threshold level. Temperature also controls and defines stages of seasonal vegetation community development that modifies surface fuel composition. Following snowmelt, which in southern Finland takes place early April (Solantie *et al*. 1996), surface fuel material consists of dead or dormant vegetation that has relatively low moisture content and responds to the atmospheric conditions in the manner of dead fuels (Brown and Simmerman 1986). The main shoot growth of the most common understory species starts early June and continues until late July (Holloway 1981, Vanninen *et al*. 1988); during this period the proportion of dead fuel load in relation to live surface fuels is at its lowest. Late in the season, plant growth slows down and a part of the live fuel load may start contributing to higher fire hazard as a result of curing (Burgan 1979, Brown *et al*. 1989).

In the generally mild fire weather conditions characteristic of Finland, changes in the dead/live proportions of fuel material caused by seasonal vegetation dynamics may be a very significant factor for fire behavior (Countryman 1974, Albini 1976). In this study, we examine the relationship between forest fire activity, the Finnish Forest Fire Risk Index (Heikinheimo *et al*. 1998, Venäläinen and Heikinheimo 2003) and the Canadian Fire Weather Index System (Van Wagner 1987, Stocks *et al*. 1989) at different stages of seasonal vegetation development. The results will facilitate the application of these fire weather indices for fire management purposes in Finland.

Material and methods

Fire data

Fire data consisted of the unpublished national Finnish fire records 1996–2003 which had been collected and sent by local fire officials to the Department of Rescue Service at the Finnish Ministry of the Interior. The information on each fire consists of date, time, location, and area burned. The events were classified as forest fires, clearing or other open area fires, and peatland fires. The reports did not include information on fire weather, fire behavior, or the intensity of suppression actions.

From 1996 through 2003, a total of 7675 forest fires reportedly occurred in Finland. The yearly average of fire occurrence was 959 fires per year and total area burned 357 ha (Table 1). The year 2002 had the highest number of fire events, nearly twice the average of the dataset, and year 1997 had the highest total area burned, nearly 1000 ha (Table 1). The years 1998, 2000, and 2001 had the lowest number of fires and total area burned (Table 1). During the two weakest fire seasons, 1998 and 2001, the total area burned was less than 100 ha (Table 1). The range of final fire size in the total data was 0 to 200 ha. The average fire size (total area burned divided by the total number of fires) was 0.37 ha (Table 1). The seasonal time span of fire occurrence ranged from the beginning of April to the end of October. On average, July presented the highest number of fire events and May the highest area burned (Table 1).

The assessment of fire weather conditions

Data on fire weather was obtained using the Finnish Forest Fire Risk Index (the FFI) and the Canadian Fire Weather Index System (the FWI System). The FFI estimates the volumetric moisture content of a 6-cm-deep organic surface fuel layer formed by live and dead moss, litter, and humus in clear-cut areas as a function of total precipitation and evaporation (Heikinheimo *et al*. 1998, Venäläinen and Heikinheimo 2003). The amount of rain retention (mm/day) in the fuel layer in relation to the total amount of rain received (mm/day) was studied in field experiments by observing weight changes in standard

Table 1. Forest fire statistics 1996–2003 for Finland.

Fire season	All fires (*N*)	Area burned (ha)	Average firesize (ha)	Month of most fires		Month of the highest area burned	
				Month	Number	Month	Area (ha)
1996	1119	344	0.31	Sep.	564	May	111
1997	1217	922	0.76	July	429	June	671
1998	256	93	0.36	May	135	May	54
1999	1171	445	0.38	Sep.	328	Sep.	173
2000	576	280	0.49	May	253	May	247
2001	541	96	0.18	July	165	June	38
2002	1745	313	0.18	Oct.	405	May	117
2003	1050	366	0.35	July	342	July	93
Mean	959	357	0.37		328		188

fuel samples at different initial water contents (Heikinheimo *et al*. 1998). For the estimation of fuel drying or wetting (DW), the ratio of the amount of water lost in relation to potential evaporation (E_{pot}) — drying efficiency (DE) — was related to the initial volumetric moisture content of the surface fuel layer based on fuel weights observed in the field experiments (Heikinheimo *et al*. 1998). As a summary the change of water in the surface layer (DW) is estimated using:

$$\mathrm{DW} = -\mathrm{DE} \times E_{\mathrm{pot}} + 5.612\left[1 - \exp\left(-\frac{\mathrm{Prec}}{5.612}\right)\right] \quad (1)$$

where Prec is the measured precipitation (mm).

For the drying efficiency (DE) the formula is

$$\mathrm{DE} = 0.757 \Big/ \left\{1 + \exp\left[2.74 - 16.67\left(W_{\mathrm{vol}} - 0.1\right)\right]\right\} \quad (2)$$

where W_{vol} is the initial volumetric moisture content of the surface fuel layer.

The calculation of potential evaporation in the current application is made using the so-called Penman-Monteith equation (e.g. Monteith 1981):

$$E_{\mathrm{pot}} = \frac{\Delta \times R_{\mathrm{n}} + \rho \times c_{\mathrm{p}} \times \left(\dfrac{1 + b \times r_{\mathrm{a}}}{\rho \times c_{\mathrm{p}}}\right) \times \left(e_{\mathrm{s}} - e\right) \Big/ r_{\mathrm{a}}}{\left[\Delta + \gamma \times \left(\dfrac{1 + b \times r_{\mathrm{a}}}{\rho \times c_{\mathrm{p}}}\right)\right] \times L} \quad (3)$$

Δ is the slope of saturated vapour pressure *vs*. temperature curve (hPa K^{-1}), R_n is the net radiation (W m^{-2}), ρ is the density of air (1.2923 kg m^{-3}), c_p is the specific heat of air (1004 J kg^{-1} K^{-1}), b is the measuring height correction multiplier (Wm^{-2} K^{-1}), r_a is the aerodynamic resistance (sm^{-1}), e_s is the saturation vapour pressure (hPa), e is the vapour pressure (hPa), γ is the psychrometer constant (0.66 hPa K^{-1}), and L is the latent heat of vaporization (2.5×10^6 J kg^{-1}). How the needed data for Eq. 3 are obtained from routine weather observations is explained by Venäläinen and Heikinheimo (2002).

The final product of the system, the FFI value, was essentially the estimated moisture content which was scaled to range between 1 and 6; 1 indicating the lowest and 6 the highest possible fire risk in terms of fuel moisture. The FFI value of 4.0 is currently being used as a threshold for generating a regional fire hazard announcement, but more extensive fuel moisture comparisons have indicated the actual critical index value to range 3.5–6.0 for different stand types (Tanskanen *et al*. 2006). The FFI is calculated every three hours (at 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00) during the fire season. In this study, we used the daily average of these eight FFI values. Using noon values would have been optimal in terms of comparability with the other indices. The noon data for the FFI, however, was not available for all study regions and study periods. Using daily averages can not be considered to cause substantial error because the FFI changes very slowly: the index never drops within a day straight from high to low fire danger or vice versa and the maximum variation in the index value within a day remains in the order of 0.2. The index values were calculated using weather data from the permanent weather stations of the national station network which is maintained by the Finnish Meteorological Institute at approximately 200 locations throughout the country (Venäläinen and Heikinheimo 2002).

The Canadian FWI System uses as input daily noon local standard time weather readings of temperature, relative humidity, 10-m wind, and 24-h precipitation, and yields as output seven indices that describe various aspects of fire behaviour (Van Wagner 1987). The seven indices are Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Build-Up Index (BUI), Fire Weather Index (FWI), and Daily Severity Rating (DSR) (Van Wagner and Pickett 1985, Van Wagner 1987). The FFMC and DMC are indicators of moisture content in fine surface fuel and loosely compacted duff (Stocks *et al*. 1989). The drying and wetting functions of the FFMC and DMC codes are based on the idea of equilibrium moisture content which assumes that for every combination of relative humidity and air temperature there is a level of moisture content that dead fuel moisture will approach and stabilize at (Nelson 2001). The rates of drying and wetting depend not only on the prevailing weather conditions but on the difference between the initial moisture content and the target equilibrium moisture content (Van Wagner 1987). The ISI estimates the combined influence of fine fuel moisture (the FFMC) and prevailing wind speed on fire spread rate (Van Wagner 1987).

The BUI combines the DMC and DC ratings of fuel moisture and represents the fraction of the fuel bed dry enough to be available for combustion (Van Wagner 1987, Stocks *et al*. 1989). The FWI code combines the ISI and BUI and is a relative measure of the potential intensity of single spreading fire in a standard fuel complex on level terrain (Stocks *et al*. 1989). The FWI code output value may range from 0 to over 50. In most regions of Canada, the FWI values 0–5 indicate low fire danger and values in excess of 22 extreme fire danger (Stocks *et al*. 1989).

The focus of this study is on the impact of short-term (daily, weekly) weather variation on fire activity. As an indicator of fire spread rate the ISI should theoretically be the best match for the daily area burned. Being based on the Fine Fuel Moisture Code that has the smallest moisture capacity of the FWI System, the ISI has most potential for detecting surface fuel moisture changes that are meaningful to fire initiation and initial spread. The FWI code is considered a good indicator of general fire danger (Van Wagner 1987, Stocks *et al*. 1989). The FWI has also been previously found as a good predictor of fire ignition potential in this fire environment (Tanskanen *et al*. 2005). The calculations of the FWI System were done using the improved standard version of 1984 (Van Wagner and Pickett 1985, Van Wagner 1987). No adjustments were made on the standard effective day-length factors because the impact of latitude on model performance is not considered significant (Van Wagner 1987). The weather data for the FWI System calculations were provided by the Finnish Meteorological Institute.

The drought code as an indicator of a long-term weather phenomenon and between-season differences is not included in this study due the shortness of the time span for which consistent weather data and fire activity records were available and the generally low occurrence of significant droughts in Finland. The FFMC was also excluded because this code can present wide variation within a single day which, not having control over the timing of fire activity or the daily index variation, would likely yield very unreliable results. The BUI as a measure of the depth of fuel layer that will potentially burn was not considered a meaningful predictor of our fire activity variables.

The impact of seasonal vegetation development

The effective temperature sum is a variable commonly used to assess the progress of the growing season and vegetation development (Heikinheimo and Lappalainen 1997). The effective temperature sum is a cumulative sum (unit: degree days or d.d.) of average daily air temperatures that exceed a chosen critical threshold temperature value, e.g. 0 °C or 5 °C. In boreal climate, the accumulation the effective temperature sum follows a sigmoidal pattern, the sum starting to increase slowly at the time of snowmelt, accumulating at the highest rate during early and mid-summer, and then slowing down and saturating during late summer and early autumn. In southern Finland, the average seasonal maximum range of the 5 °C temperature sum is 1100–1300 degree days (Solantie 1990).

The daily values of the effective temperature sum (T_{sum}) for this study were calculated using equation:

$$T_{sum} = \sum_{d=1}^{n} \left(T_d - T_{min}\right) \quad \text{if } T_d \geq T_{min} \left(°\text{C}\right) \qquad (4)$$

where T_d is the daily mean temperature, and the required minimum temperature T_{min} is 5 °C. We chose three cut points of the effective temperature sum to define stages of the fire season when the fire danger prediction ability of fire weather indexes might be altered due to vegetation development. The first distinct stage of the growing season in terms of surface fuel composition is the period after snowmelt when new vegetation has not fully started to grow and surface fuel mainly consists of dead fuel material. The temperature needed to start the seasonal growth varies to some extent among the common Finnish understory plant species (e.g. Havas and Kubin 1983, Heikinheimo and Lappalainen 1997). In this study, we use effective temperature sum values of 0 and 50 as boundaries for the initial slow-growth part of the fire season. When the daily temperatures after late spring reach consistently higher values, the growth of the understory vegetation is accelerated. The height growth of *Vaccinium myrtillus* reaches its maximum at effective temperature sum (calculated using 0 °C as the threshold value) of 300–400 d.d. and *Vaccin-*

ium vitis-idaea slightly later at total temperature sum of 500–600 d.d. (Havas and Kubin 1983). After the growth acceleration phase, the phytomass in the new shoots of *Vaccinium myrtillus* increases in northern Finland until the beginning of August after which leaves begin to age and drop (Havas and Kubin 1983). In this study, we use an effective temperature sum (+ 5 °C threshold) value of 250 d.d. to mark the point where dwarf shrubs would have mostly reached the maximum vertical shoot growth and 900 d.d. to mark the beginning of the late season dieback of understory vegetation.

Fire activity indicators

The fire potential or fire danger that fire weather indices assess can not be measured as such but they are usually described by observations of fire activity (Andrews *et al*. 2003). Number of fires and area burned are the most often used dependent variables in analyzing the performance of fire danger rating systems (e.g. Krusel *et al*. 1993, Andrews *et al*. 2003).

The occurrence of a single fire on a certain day may not provide accurate reflections of fire danger in a fire environment such as Finland where nearly 90% of ignitions are human-caused, and fires are efficiently detected and reported regardless of final fire size if the ignition sustains itself long enough to cause a fire alarm. As a demonstration of this, 11% of the fire events in our fire database had a reported final area burned of less than 1 m^2. The occurrence of several fires on the same day is a more plausible indicator of high fire potential and ignition even though the significance is still to some extent inflated by the accuracy of reporting and human factors involved with fire initiation.

Large daily area burned and large fires are dependent on the occurrence of suitable fire danger conditions also in human-dominated fire environment. Using these variables in the statistical performance evaluation of fire weather index systems is, however, problematic due to the low number of actual large fires. Large fires are generally defined as fires that are difficult or impossible to control and that within the area and time period of interest account for very small proportion (2%–5%) of fire events but are responsible for the majority (up to 95%–98%) of total seasonal area burned (Weber and Stocks 1998). Thresholds for a large daily area burned or a large fire can be adjusted to increase the number of observations to a level that enables statistical analysis.

Analyzing fire activity in relation to fire weather and seasonal vegetation development

The co-variation of fires, fire weather indices, and effective temperature sum was examined in three study areas in the southern half of Finland (Fig. 1) in 1996–2003. A reported fire was included in this dataset if it occurred within a 140 km × 140 km rectangle surrounding the permanent weather stations in Kauhava (63°07´N, 23°02´E), Jyväskylä (62°24´N, 25°40´E), and Tampere (61°25´N, 23°37´E) (Fig. 1). For Kauhava region, the required independent variables were available for years 1996–2003, for Jyväskylä region for years 1996–2001, and for Tampere region for years 2002–2003. The combined fire dataset for the three regions in those years consisted of 639 fires which ranged in size from 0 to 25 ha and burned a total of 282 ha. The average daily area burned was 0.44 ha. Up to 90% percent of the reported fires were smaller than 1.0 ha and 80% smaller than 0.5 hectares. Days having area burned over 1.0 hectares accounted for 74% of total area burned and days burning over 0.5 ha for 89% of total area burned.

The occurrence of fire can be considered a binary variable; a fire can either occur (value = 1) or be absent (value = 0). Following the methodology used by Martell *et al*. (1987) and Andrews *et al*. (2003), the fire records were analyzed by determining the occurrence or absence of a fire-day (value for a day = 1 if one fire occurred, otherwise 0), a multiple-fire-day (value for a day = 1 if more than one fire occurred, otherwise 0), and a large-fire-day (value for a day = 1, if area burned is ≥ A (large fire), otherwise 0). In these data, the threshold for a large-fire-day as determined by the 90th percentile of the total area burned was 0.5 ha.

The relationship between a qualitative binary response and a single predictor variable often assumes an S-shape (Mendenhall and Sincich 2003). This type of dependency can be analyzed using logistic regression models (Mendenhall and Sincich 2003). In this study, the analysis was carried out using the binary logistic regression function of SPSS Version 12.0.1 which applies logit transformation:

$$\mathrm{Logit}(p) = \ln\left(\frac{p}{1-p}\right) = a + bx \tag{5}$$

and consequently, the probability p is calculated as:

$$p_{\mathrm{event}} = \frac{1}{1+e^{(-a-bx)}} \tag{6}$$

where *event* is fire activity (fire-day, multiple-fire-day, or large-fire-day), covariate x is the FFI, FWI, or ISI, and a and b are the output parameters of the model fitting.

At first, logistic regression modeling was carried out for all-season data to identify the general relationship of fire activity variables on FFI, FWI, and ISI. Then logistic regression models were formed for four different periods of the growing season using the effective temperature sum values of 50, 250, and 900 as separation thresholds for the new datasets.

The observed probabilities of fire activity within fixed intervals of fire weather index range were calculated and compared with the probabilities given by the respective regression model. The observed fire activity probabilities were calculated as averages for the FFI index ranges of 1.0–2.0, 2.01–3.0, 3.01–4.0, 4.01–5.0, and 5.01–6.0. For the ISI, the averages were calculated within index ranges of 0–2.0, 2.01–4.0, 4.01–6.0, 6.01–8.0, and 8.01–16.0. For the FWI, the respective index ranges were 0–6.0, 6.01–12.0, 12.01–18.0, 18.01–24.0, and 24.01–36.0. For the open-ended ISI and FWI codes, the averages of fire activity were not calculated for the total range of the observed index value variation (the observed maximum was 31.0 for the ISI and 51.0 for the FWI) due to the uneven distribution and low number of the extremely high index values.

We observed the index-specific model probability ranges for fire-day, multiple-fire-day, and large-fire-day as an indicator of the overall goodness of an index for fire activity prediction (Andrews *et al.* 2003). A good logistic regression model should yield a wide probability range and start from near-zero probabilities at low index values (Andrews *et al.* 2003). Additionally, the Hosmer-Lemeshow goodness-of-fit statistic, χ^2, was calculated to assess the validity of logistic regression models. The Hosmer-Lemeshow statistic is calculated by comparing the observed probability with the expected probability within each decile of risk (Hosmer and Lemeshov 2000). It is a robust indicator when used to evaluate models based on continuous covariates such as a range of fire weather index values. Another statistical indicator used in the analysis is a pseudo R^2 which resembles the standard coef-

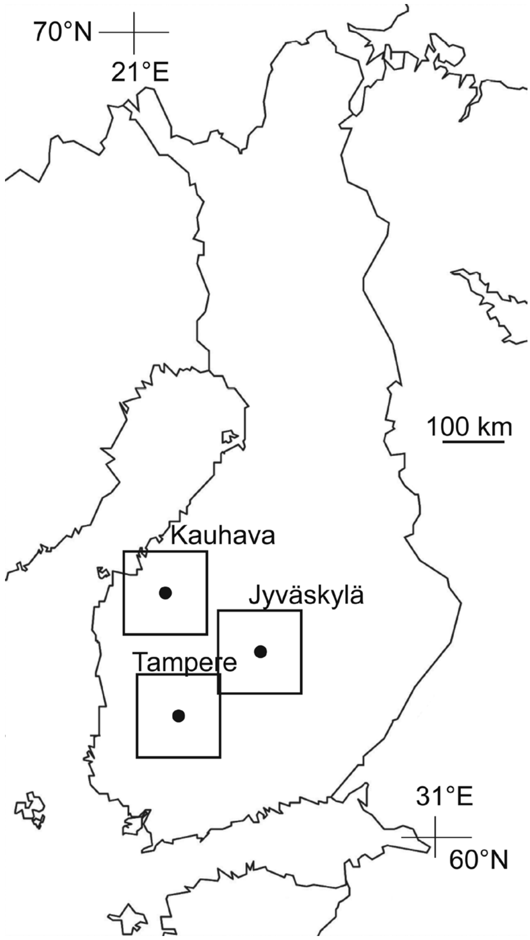

Fig. 1. Map of Finland and the study areas around weather stations in Kauhava, Jyväskylä, and Tampere.

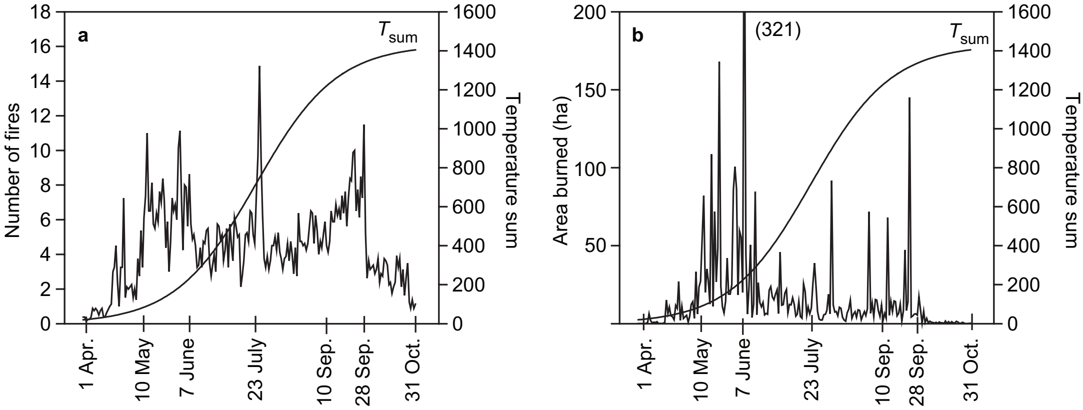

Fig. 2. (**a**) Average daily number of reported forest fire events (left axis) and the accumulation of effective temperature sum (right axis) in Finland (340 000 km²) during fire seasons 1996–2003. (**b**) Average daily burned area (left axis) and the average effective temperature sum (right axis) in Finland during fire seasons 1996–2003.

ficient of determination but due to the mechanics of logistic regression usually returns very small values (Hosmer and Lemeshow 2000). In this study, we report the SPSS ver. 12.0.1 test output Nagelkerke's R^2 for each model.

Summary of the steps of the analysis

1. Preliminary analysis of the total national fire data to find seasonal trends in the number of fires and area burned.
2. Calculating daily values of the effective temperature sum, the FFI and the FWI System codes to the three study locations Tampere, Kauhava, and Jyväskylä based on weather data from permanent weather stations.
3. Screening of reported fire events to 140 km × 140 km rectangles surrounding the three study areas.
4. Transforming data into binary datasets showing the occurrence or absence of fire-day, multiple-fire-day, and large-fire-day for every day of the fire season.
5. Dividing the three regional fire datasets into phases of absent live fuel load, increasing live fuel load, maximum live fuel load, and declining live fuel load based using the effective temperature sum values of 0, 50, 250, and 900 respectively as the starting points for each phase, respectively.
6. Running a logistic regression analysis for the probability of fire-day, multiple-fire-day, and large-fire-day as a function of the FFI value and as a function of the FWI System's ISI, and FWI code value in different phases of the fire season.
7. Comparison of observed and modeled probabilities of fire activity and assessment of the reliability of the logistic regression models.
8. Determining the relationship between different fire weather index values and fire activity in general and at different phases of the growing season.

Results

Seasonal trends of fire activity in the total national fire data

The total number of forest fire incidents in Finland presented three major peaks (Fig. 2a). The first of these occurred during the early fire season, from 10 May to 7 June, at the average effective temperature sum of below 230 (Fig. 2a). The second and the highest one took place on 21–25 July, and the third on 10–28 September, roughly at the temperature sum of 1200 (Fig. 2a). When average fire frequency was 4.5 fires per day for the total season, at highest the number of reported ignitions was 14.9 per day during the brief peak in mid-July (Fig. 2a).

The highest daily area burned values co-occurred with the first ignition peak between 10 May and 7 June at the temperature sum of 150–230 and declined from then on (Figs. 2a and b). The seasonal average of daily burned area was 1.7 ha for the total period of April–October. Average fire size during the first high-activity period from 8 May to 15 June was 36.6 ha and during the second from 27 August to 22 September, 16.6 ha.

The average characteristics of the effective temperature sum and fire weather indices in the three study regions

The effective temperature sum on average reached the value of 50 during the second week of May (Fig. 3a). The next analysis threshold value, 250 d.d., was at earliest reached at the beginning of June and at the latest exceeded mid-June (Fig. 3a). The third threshold of 900 d.d. was met at the earliest right after mid-July and at the latest at the beginning of September (Fig. 3a). The seasonal effective temperature sums normally saturated in early September (Fig. 3a), the final reading of it ranging between 1000 and 1500 (Fig. 3a).

The monthly averages of the FFI, ISI, and FWI did not differ between core fire season months May–September but presented significantly lower values during the season boundary months April and October (Fig. 3b). Excluding the boundary months, the fire season averages ranged 2.7–3.0 for the FFI, 8.4–10.5 for the FWI, and 3.6–5.3 for the ISI. The average value of FFI was 1.7 for April and 1.3 for October and the average of FWI was 4.5 and 2.0 April and October, respectively (Fig. 3b).

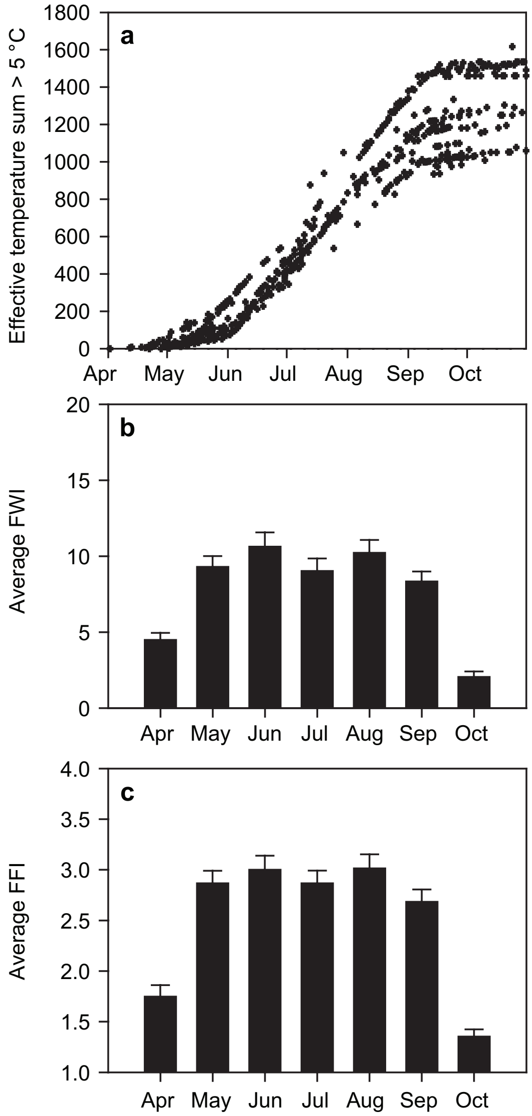

Fig. 3. (**a**) The daily accumulated effective temperature sum > 5 °C and the monthly averages of (**b**) the FWI code and (**c**) the FFI in Kauhava, Tampere, and Jyväskylä 1996–2003.

Fire activity as a function of fire weather indices

In the FFI-based logistic regression models, the probability range for a fire-day was 5%–55%, and for a multiple-fire-day and a large-fire-day 0%–25% (Fig. 4a). In the FWI-based models, the respective maximum probabilities were 5%–80% for a fire-day and 0%–50% for multiple-fire-day and large-fire-day (Fig. 4b). Having the ISI as a predictor, the fire activity probabilities for fire-day ranged 5%–85% when the index ranged from 0 to 31.3 (not shown). The total range of predicted fire activity probabilities was much wider for the FWI and ISI than for the FFI. All models yielded equally low, 5%, probabilities of fire activity at low index values but differed in their predictions at high index values: the maximum probabilities remained much lower in the FFI-based models than in the FWI- and ISI-based models indicating that the FFI was less accurate at picking up the conditions of highest fire danger.

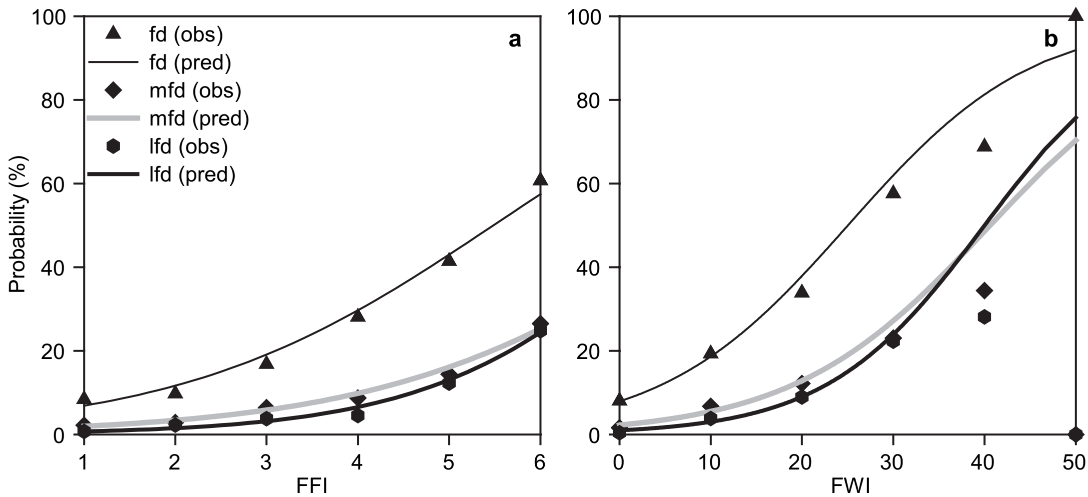

Fig. 4. The observed and predicted (Eq. 5) probabilities of fire-day (fd), multiple-fire-day (mfd), and large-fire-day (lfd) as a function of (**a**) the FFI and (**b**) the FWI.

The observed and predicted fire activity levels related well throughout the observed FFI index range. The FWI-based model probabilities were slightly higher than actual fire activity at index values of above 20 (Fig. 4b). At the highest FWI values 40–50, the observations and the model estimates were far apart probably due to the low number of observations, only 0.3% (N = 10) of days qualifying for this class in contrast to 6.1% of the days falling into the highest category of the FFI > 5.

The FFI was the best predictor of fire activity based on Hosmer-Lemeshov goodness-of-fit test which gave support to FFI-based models in all three fire activity categories (Table 2). Goodness-of-fit was assessed statistically significant for ISI-based multiple-fire-day-model but poor for all FWI-based models (Table 2). A very low amount of variation in the fire activity was explained by any of the models Nagelkerke's pseudo R^2 range being only 0.08–0.19 (Table 2). The analysis of residuals showed that all models underestimated fire activity because fires commonly occurred at lower index values which in the models produced a zero-category response.

Fire activity as a function of fire weather indices during different stages of the growing season

Adding the effective temperature sum as a continuous covariate into previously tested fire weather index-based logistic regression models produced mixed results. The pseudo coefficient of determination was in most cases improved slightly, but the odds ratio of the temperature sum remained meaningless in all models (Table 2). The incorporation of temperature sum added goodness-of-fit in the Hosmer-Lemeshov test when the ISI was used as predictor for fire-day and large-fire-day, and the FFI to predict the probability of large-fire-day (Table 2).

Using the four temperature sum-based stages of the growing season as separate datasets for logistic regression analysis generally improved the goodness-of-fit, and increased pseudo R^2, and odds ratio values (Table 2). According to the Hosmer-Lemeshov statistic the goodness-of-fit was best during season stage B for all other models but ISI-fire-day and ISI-multiple-fire-day (Table 3). The poorest fit occurred during the last period of the season (Table 3). Fire weather indices were able to explain the highest amount of variation in fire activity during the second period of the growing season (T_{sum} = 50.1–250) pseudo R^2 values ranging 0.19–0.31 (Table 3). The final period of the growing season had the lowest pseudo R^2 for fire-day and multiple-fire-day (Table 3). The FFI odds ratio varied greatly between seasonal stages and was at its highest in the large-fire model during season stage B. For the FWI- and ISI-based models the seasonal variation in odds ratio was minor (Table 3) which is likely due to different scaling of these indices in comparison to the FFI.

When fire danger was rated as low (FFI below 2.5, FWI below 10.0, and ISI below 3.0) the probabilities of fire-day ranged 4%–18% (Table 4). For multiple-fire-day, the respective probability range was 1%–6% and for large-fire-day 0.3%–1% (Table 4). For days having a high fire danger rating (FFI above 4.6, FWI above 20.0, and ISI above 9.0), the probabilities ranged 31%–63% for fire-day, 11%–30% for multiple-fire-day, and 8%–24% for large-fire-day (Table 4).

Fire-day probabilities were generally highest during the final stage of the growing season (T_{sum} > 900) (Table 4, Figs. 5a, 6a, and 7a). In the FFI-based probability models, the other stages of the growing season did not differ from each other (Fig. 5a). In the FWI-based models, the final stage of the season had highest fire-day probability at index values below 25 and the third stage of the season (T_{sum} = 250–900) had consistently lowest fire-day probability (Fig. 6a). In the ISI-models, the probability of fire-day was highest during the final stage of the fire season and lowest during the first stage throughout the index range (Fig. 7a).

Large-fire-day probabilities showed little variation between season stages in the FFI-based models (Fig. 5b). At the highest FFI values (above 4.5), the third stage of the season pre-

Table 2. Logistic regression model statistics for dependent variables fire-day (fd), multiple-fire-day (mfd), and large-fire-day (lfd) using fire weather indices (FFI, FWI, ISI) and the effective temperature sum (T_{sum}) as predictors. *B* = calculated equation parameter, SE = standard error of the parameter, Wald = the value of a Wald test statistic with 1 degree of freedom (*$p < 0.05$), Exp(*B*) = odds ratios for the independent variables, with the 95% confidence interval (95% C.I.), Pseudo R^2 = indicator of the amount of variation in the dependent variable explained by the model, value given is Nagelkerke's R^2, and Hosmer-Lemeshov χ^2 (the value of the Hosmer-Lemeshov test of model fit) (*p < 0.05). In the last two columns (R^2 and χ^2) the upper value of each pair is the test result for models using only a fire weather index as a predictor and the lower for models using both fire weather index and the effective temperature sum as predictors.

	Predictor	$B \pm$ SE	Wald	Exp(*B*) (lower and upper 95% CI)	Pseudo R^2	Hosmer-Lemeshov χ^2
fd	Constant	–3.750 ± 0.143	691.6*	0.024		
	FFI	0.595 ± 0.033	322.0*	1.813 (1.699, 1.935)	0.17	8.8*
	Tsum	0.001		1.001 (1.001, 1.001)	0.20	22.7
	Constant	–2.988 ± 0.108	772.2*	0.050		
	FWI	0.100 ± 0.005	343.7*	1.105 (1.094, 1.117)	0.18	16.5
	Tsum	0.001	68.4*	1.001 (1.001, 1.001)	0.21	23.3
	Constant	–3.204 ± 0.121	700.3*	0.041		
	ISI	0.211 ± 0.013	282.1*	1.234 (1.205, 1.265	0.12	18.9
	T_{sum}	0.001	129.8*	1.001 (1.001, 1.001)	0.18	14.0*
mfd	Constant	–5.099 ± 0.236	467.4*	0.006		
	FFI	0.571 ± 0.051	126.5*	1.771 (1.603, 1.956	0.11	3.3*
	T_{sum}	0.001	34.5*	1.001 (1.001, 1.001)	0.14	24.0
	Constant	–4.411 ± 0.182	585.5*	0.012		
	FWI	0.095 ± 0.007	171.6*	1.099 (1.084, 1.115)	0.13	22.2
	T_{sum}	0.001	35.3*	1.001 (1.001, 1.001)	0.16	23.0
	Constant	–4.558 ± 0.200	519.8*	0.010		
	ISI	0.191 ± 0.016	133.9*	1.210 (1.171, 1.250)	0.08	15.0*
	T_{sum}	0.001	63.3*	1.001 (1.001, 1.001)	0.13	25.0
lfd	Constant	–5.750 ± 0.308	348.1*	0.003		
	FFI	0.763 ± 0.068	126.0*	2.144 (1.877, 2.449)	0.16	11.6*
	T_{sum}	0.000	0.1	1.000 (1.000, 1.000)	0.16	13.8*
	Constant	–4.683 ± 0.212	488.1*	0.009		
	FWI	0.116 ± 0.009	177.6*	1.112 (1.104, 1.142)	0.19	17.6
	T_{sum}	0.000	0.3	1.001 (1.001, 1.001)	0.19	21.1
	Constant	–4.867 ± 0.232	439.6*	0.008		
	ISI	0.228 ± 0.019	146.5*	1.251 (1.210, 1.303)	0.15	17.8
	T_{sum}	0.001	10.9*	1.001 (1.000, 1.001)	0.16	11.4*

sented distinctly higher large-fire-day occurrence whereas the second stage remained at the lowest level. In the FWI-models, the initial stage of the season had highest large-fire-day probability within the index range available for analysis (Fig. 6b) and the second stage presented lowest probabilities. In the ISI-models, the large-fire-day probability was consistently highest during

Table 3. Logistic regression model statistics: χ^2 value of the Hosmer-Lemeshov test of model fit (*$p < 0.05$), Nagelkerke's R^2, and Odds ratio Exp(B) for the different stages of growing season defined by the effective temperature sum ranges A: 0–50, B: 50.1–250, C: 250.1–900, and D: > 900. Fire weather indices FFI, FWI, and ISI used as independent variables for modeling variation in the probabilities of fire-day (fd), multiple-fire-day (mfd), and large-fire-day (lfd). The best model validity result within the four seasonal stages is indicated with boldface.

Model		Hosmer-Lemeshov χ^2				Nagelkerke's R^2				Odds ratio Exp(B)			
		A	B	C	D	A	B	C	D	A	B	C	D
FFI	fd	16.4	**2.6***	8.6*	5.7*	0.16	**0.22**	0.21	0.13	1.88	2.06	**2.11**	1.60
	mfd	12.5	**9.5***	11.4*	14.0	0.14	**0.19**	0.13	0.07	2.00	**2.37**	1.99	1.51
	lfd	10.5*	**2.3***	8.8*	15.3	0.13	**0.21**	0.21	0.18	1.97	**3.53**	2.73	2.24
FWI	fd	8.8*	**8.1***	13.0*	16.3	0.18	**0.27**	0.17	0.15	**1.16**	1.12	1.10	1.10
	mfd	18.0	**5.5***	10.8*	32.4	0.18	**0.27**	0.11	0.11	**1.17**	1.14	1.08	1.09
	lfd	19.9	**4.2***	7.1*	10.9*	0.16	**0.31**	0.19	0.22	1.16	**1.18**	1.12	1.14
ISI	fd	8.5*	15.9*	**4.9***	8.8*	0.14	**0.28**	0.12	0.10	1.23	**1.27**	1.20	1.22
	mfd	10.4*	10.4*	**8.3***	12.6*	0.13	**0.25**	0.06	0.06	1.24	**1.26**	1.15	1.18
	lfd	12.7*	**3.7***	20.8	5.5*	0.12	**0.22**	0.10	0.15	1.24	**1.24**	1.19	1.33

Table 4. The observed and predicted probabilities of fire activity (fire-day, multiple-fire-day, and large-fire-day) in the lowest and the highest ranges of the FFI, FWI, and ISI for the effective temperature sum ranges A: 0–50, B: 50.1–250, C: 250.1–900, and D: > 900. The highest seasonal probability of fire activity within each index range indicated with boldface.

Index range	T_{sum} range	No. of days	F-days (%)		Mf-days (%)		Lf-days (%)	
			Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
FFI 1.0–2.5	A	531	5.5	6.4	1.3	2.1	0.9	**1.3**
	B	248	6.5	7.5	1.2	1.9	**2.4**	1.1
	C	424	5.9	6.9	2.4	2.3	1.2	1.2
	D	591	**14.4**	**13.7**	**3.9**	**4.0**	0.7	1.1
FFI 4.6–6.0	A	52	30.8	41.3	13.5	15.6	9.6	**17.3**
	B	82	47.6	45.5	18.3	14.3	13.4	15.0
	C	143	46.2	43.3	**19.6**	17.0	**18.9**	16.3
	D	103	**54.4**	**62.0**	15.5	**26.6**	16.5	16.0
FWI 0–10.0	A	579	5.4	7.8	0.7	2.4	0.9	**1.5**
	B	327	8.3	9.1	1.2	2.0	**1.5**	1.0
	C	606	9.4	8.8	3.0	2.6	1.2	1.2
	D	691	**17.2**	**16.0**	**4.2**	**4.3**	0.4	1.1
FWI 20.0–51.0	A	24	33.3	43.4	12.5	18.9	8.3	**24.0**
	B	81	**55.6**	47.6	**21.0**	16.2	17.3	17.7
	C	137	46.0	46.5	19.0	20.0	**19.7**	20.1
	D	93	54.8	**63.3**	17.2	**29.9**	17.2	19.6
ISI 0–3.0	A	318	3.5	4.6	0.6	1.5	0.3	0.7
	B	255	6.3	7.5	0.8	1.8	0.4	0.9
	C	507	9.3	8.5	3.0	2.7	**1.4**	**1.3**
	D	602	**18.0**	**15.5**	**5.5**	**4.6**	1.0	**1.3**
ISI 9.0–31.0	A	88	35.2	30.8	12.5	11.2	9.1	12.3
	B	102	**55.9**	43.0	19.6	13.4	19.6	14.4
	C	96	44.8	46.2	15.6	19.1	12.5	20.3
	D	45	55.6	**62.9**	**22.2**	**28.8**	**22.2**	**20.5**

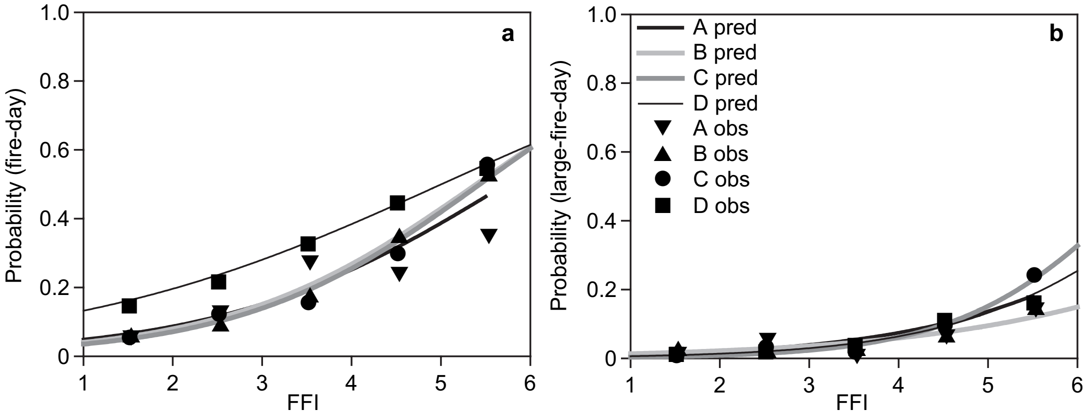

Fig. 5. The observed and predicted (Eq. 5) probabilities of (**a**) fire-day (fd) and (**b**) large-fire-day (lfd) as a function of FFI at different stages (A, B, C, D) of fire season. Effective temperature sums: A: 0–50, B: 50.1–250, C: 250.1–900, and D: > 900. The observed values have been calculated as averages for the FFI ranges of 0–1.0, 1.01–2.0, 2.01–3.0, 3.01–4.0, 4.01–5.0, and 5.01–6.0.

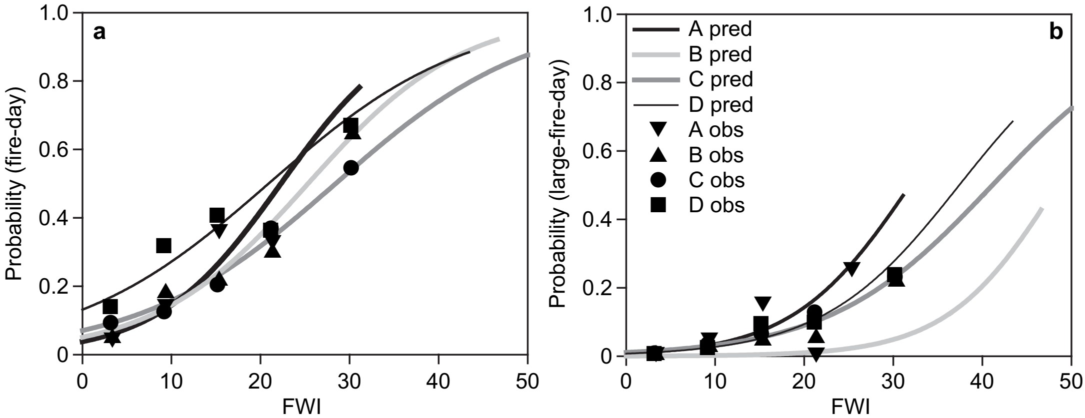

Fig. 6. The observed and predicted (Eq. 5) probabilities of (**a**) fire-day and (**b**) large-fire-day as a function of FWI at different stages (A, B, C, D) of fire season. Effective temperature sums: A: 0–50, B: 50.1–250, C: 250.1–900, and D: > 900. The observed values have been calculated as averages for the FWI ranges of 0–6.0, 6.01–12.0, 12.01–18.0, 18.01–24.0, and 24.01–36.0.

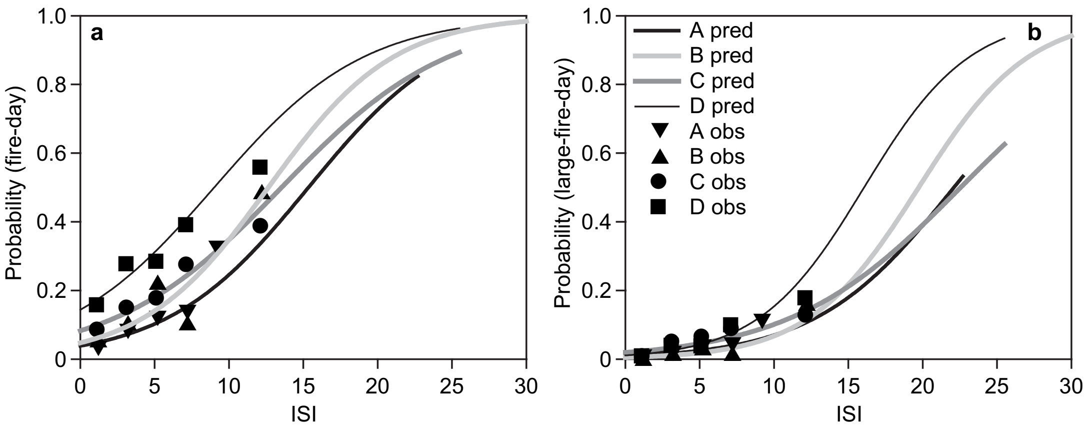

Fig. 7. The observed and predicted (Eq. 5) probabilities of (**a**) fire-day and (**b**) large-fire-day as a function of ISI at different stages (A, B, C, D) of fire season. Effective temperature sums: A: 0–50, B: 50.1–250, C: 250.1–900, and D: > 900. The observed values have been calculated as averages for the ISI ranges of 0–2.0, 2.01–4.0, 4.01–6.0, 6.01–8.0, and 8.01–16.0.

the final part of the season and lowest during the initial part (Fig. 7b). The comparison of observed class averages and modeled fire probabilities as a function of the FWI and ISI was not possible within higher index ranges due to a low number of observations (Figs. 6a, b and 7a, b).

Discussion

Seasonal distribution of fire activity in national data

In the total national data, the daily number of reported ignitions formed three major peaks during the fire season whereas daily area burned was highest early in the season, from late May through early June, and mainly decreased from then on. Lacking case-specific information on the causes of ignition, we were unable to define seasonal trends for different causes in the manner of earlier studies on people-caused fires (Martell *et al.* 1987). Generally, the ignitions in Finland are almost 90% human-caused and 70% of all ignitions result from careless handling of fire e.g. in the form of campfires, cigarettes, silvicultural slash burning, or trash burning (Pronto database, Finnish Ministry of the Interior; Larjavaara *et al.* 2005). In light of general statistics and fire use traditions, the earliest ignition peak is likely to contain the majority of fires originated from silvicultural slash burning and burning of cured vegetation and trash. The mid-season peak in numbers of fires coincides with the peak of lightning-caused fires (Larjavaara *et al.* 2005). The final peak around September occurs at the time of the year when people involved with hunting and various gathering activities fill the forests and are likely to contribute to fire occurrence by lighting campfires.

Based on earlier fire records, the highest area burned in late May which was slightly unexpected. According to fire occurrence studies (mainly years 1900–1950), the three most active fire months in Finland have been July, June, and August, in this order and May has been considered a marginal part of the fire season (Saari 1923, Kalela 1937, Franssila 1959, Laitakari 1960). A shift in fire activity towards the early fire season has been predicted to be the primary effect of the climate change in the continental parts of the boreal zone (Stocks *et al.* 1998). In Finland, spring mean temperatures have increased significantly during the 20th century (Tuomenvirta and Heino 1996) which supports the observations on earlier start of the fire season. However, since the yearly area burned and the average fire size are currently only a fraction of those observed at the beginning of the 20th century (Parviainen 1996) reliable comparisons between past and present seasonal trends are difficult to carry out.

The highest area burned during the early part of the season would be in accordance with model-based predictions for this region (Larjavaara *et al.* 2004) and with the knowledge that curing of live surface fuels in this fire environment is not a factor that would substantially increase fire danger late in the season. Gravimetric moisture content in some *Vaccinium* spp. has been found to decrease from 134% in the early summer to 105% in the end of the summer (Loomis and Blank 1981). By the time the seasonal shoot growth in *Vaccinium myrtillus* and *Vaccinium vitis-idaea* stops and moisture content of plant tissue decreases, other fire conditions have already become less optimal e.g. due to increased formation of dew and decreasing evaporation as a result of less solar radiation reaching the forest floor (Bonan 2002).

The overall ability of fire weather indices to explain fire activity

The match between the average observed and modeled fire activity probabilities was generally good. The predicted probability ranges for all observed fire activity variables remained lower for the FFI-based models than in the FWI- and ISI-based models indicating that the latter indices would be a better prediction tool (Andrews *et al.* 2003). In the statistical validity analysis without season stage separation, the FFI-based probability models achieved slightly better results than the FWI and the ISI. Making reliable comparisons of model performance is, however, difficult due to different output ranges of these indices. The FFI has a fixed upper limit (6.0) and its full operational range was covered by a reasonable number of observations in this study. It was complicated to define comparable value ranges for the FWI and ISI because these open-ended codes had quite uneven index value distributions at higher index value levels. This feature also made it difficult to make reliable comparisons between the observed and the predicted fire activities at higher FWI and ISI values.

The test results of the logistic regression model performance analysis being somewhat poor was likely due to the nature of the studied phenomenon: fires occur relatively frequently at low fire index values because of geographic inaccuracy of the indices and on the other hand days having high fire weather index values do not necessarily experience fires. The pseudo R^2 values remained at a very low level for all our models without season stage separation in comparison to results in other fire logistic regression model studies (Martell *et al* 1987, Andrews *et al*. 2003).

The influence of seasonal vegetation development on model performance

The incorporation of seasonal vegetation development via effective temperature sum as a continuous covariate did not improve the fit between fire activity variables and fire weather index levels likely due to too few replications at the occurred wide range of temperature sum values. Applying the sub-dataset separation based on temperature sum threshold values of 50, 250, and 900 degree days yielded higher fire occurrence probabilities for the final stage of the growing season and significantly better model performance during mid-stages of the growing season.

The modeled probabilities of fire-day and multiple-fire-day were for all fire weather indices highest during the final period of the fire season, T_{sum} > 900 d.d., and differed little between the other stages of the season. Large-fire-day probabilities in the FFI- and FWI-models were highest during the first two stages of the growing season whereas the ISI-models assigned the highest large-fire-day probability to the final stage of the season.

The highest peak in the area burned during the early part of the fire season, present in the total national data, was not very prominent in this analysis. This was likely caused by having to set the threshold for large-fire-day at a fairly low value and, on the other hand, dealing with a reduced dataset which may not have included many of the larger fires of the national data. The last part of the fire season came across as a much more active part of the fire season than expected taking into account that curing of understory vegetation mainly takes place after weather conditions have become a limiting factor (Drebs *et al*. 2002). The occurrence of fires at low fire weather index values was highest during the final period of the season (Table 3). The area burned, however, remained minimal indicating that prevailing conditions were unfavorable for fire spread.

The significance of the tested fire weather indices as explanatory variables was highest during the mid-season. During initial and final parts of the season, fire weather index-based regression models were in many cases insignificant. This is contradictory to the assumption that higher dead fuel proportion would generally increase the inter-dependency of fire activity and fire weather. The FFMC, that estimates moisture content in the uppermost dead fine fuels and is the fastest reacting code of the FWI System, has been the most significant predictor of spring fire activity in other fire activity modeling studies (Martell *et al*. 1989). In this study, the ISI, which is based on the FFMC, was expected to predict fire activity more reliably during spring and autumn. The ISI, however, did not outperform the two slower indices at any point of the fire season.

The FFI was able to model fire activity surprisingly well given that this index is more suitable for assessing fire intensity than ignition or fire spread potential. Based on a 6-cm-thick layer of surface fuel (Heikinheimo *et al*. 1998, Venäläinen and Heikinheimo 2003) the FFI drying function is relatively slow to react to precipitation and causes the index to stay at high levels after flammability has already decreased. Additionally, the FFI excludes the impact of wind on fire spread which is a feature included in the FWI and ISI (Van Wagner 1987). The performance of the FFI during the early and late season fuel conditions could potentially be improved by making index calculations for a thinner layer of surface fuel, for example using a 3-cm-layer like experimentally done in a study of Larjavaara *et al*. (2004).

Conclusions

The FFI, FWI, and ISI were all able to model fire-activity in a satisfactory manner. The probability of fire ignitions was clearly highest during the final part of the fire season whereas the probability of large fires was highest during the early parts of the season. The ability of the FFI, FWI, and ISI to explain fire activity was best during the active part of the growing season when live vegetation dominates surface fuel layers and poor during early and late parts of the fire season when the proportion of dead fuel is highest. To assess the validity of fire danger ratings generated by the FFI, forest and fire managers should take note of the stage of the growing season and dead/live fuel proportions in the area of interest. The performance of the FFI during the early and late fire season could potentially be improved by using a thinner surface fuel layer as a basis for the fuel moisture calculations.

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